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(54) **METHOD AND DEVICE FOR MARINE SEISMIC ACQUISITION**

(75) Inventors: **Fabrice Mandroux**, Montrouge (FR);  
**Alexandre Lenart**, Paris (FR)

(73) Assignee: **CGGVERITAS SERVICES SA**, Massy (FR)

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(52) **U.S. Cl.**  
CPC ..... **G01V 1/3808** (2013.01)

(58) **Field of Classification Search**  
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USPC ..... 367/16, 20  
See application file for complete search history.

(56) **References Cited**

#### U.S. PATENT DOCUMENTS

6,285,956 B1 \* 9/2001 Bennett et al. .... 702/14  
6,484,100 B1 \* 11/2002 Zuurbier et al. .... 702/3  
7,400,552 B2 7/2008 Moldoveanu et al.

8,205,711 B2 6/2012 Hopperstad et al.  
2003/0067842 A1 4/2003 Sukup et al.  
2007/0159921 A1 7/2007 Regone et al.  
2007/0165486 A1 \* 7/2007 Moldoveanu et al. .... 367/15  
2008/0285381 A1 11/2008 Moldoveanu et al.  
2009/0122640 A1 5/2009 Hill et al.  
2010/0027374 A1 2/2010 Moloveanu et al.

(Continued)

#### FOREIGN PATENT DOCUMENTS

WO 02/25315 A2 3/2002  
WO 2009/092069 A1 7/2009

(Continued)

#### OTHER PUBLICATIONS

Buia et al., "Shooting Seismic Surveys in Circles," Oilfield Review, Autumn 2008, pp. 1-31, Schlumberger, USA.\*

(Continued)

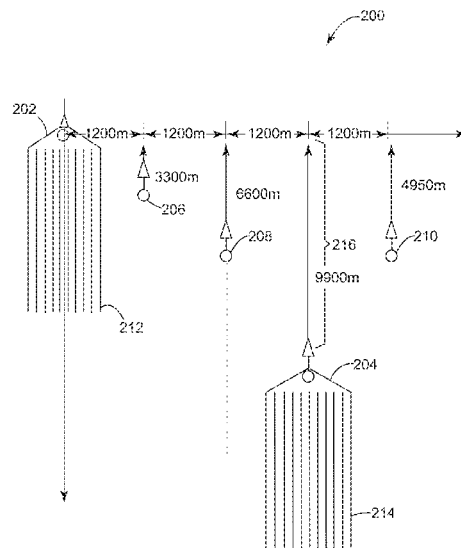
*Primary Examiner* — Daniel L Murphy

(74) *Attorney, Agent, or Firm* — Patent Portfolio Builders PLLC

(57) **ABSTRACT**

Methods and systems for improving azimuth distribution in a seismic acquisition system are described. A survey acquisition system includes a plurality of streamers towed by a plurality of streamer vessels, including a first streamer vessel and a second streamer vessel and a plurality of sources towed by a plurality of source vessels. The plurality of streamer vessels and plurality of source vessels are configured relative to one another such that the plurality of source vessels are positioned at one or more predetermined inline distances behind a portion of the first streamer vessel and are also positioned at one or more predetermined inline distances in front of a portion of the second streamer vessel. The plurality of streamer vessels and plurality of source vessels are also spaced apart from one another in a cross-line direction.

**31 Claims, 13 Drawing Sheets**



(56)

**References Cited**

## U.S. PATENT DOCUMENTS

2011/0158044	A1	6/2011	Moldoveanu et al.
2011/0199857	A1	8/2011	Garden
2012/0002503	A1	1/2012	Janiszewski et al.
2012/0033525	A1	2/2012	Abma et al.
2012/0320711	A1	12/2012	Hite

## FOREIGN PATENT DOCUMENTS

WO	2011/057324	A1	5/2011
WO	2011/082308	A2	7/2011

## OTHER PUBLICATIONS

Robert Dowle et al., "Uses of Wide-Azimuth and Variable-Depth Streamers for Sub-Basalt Seismic Imaging", First Break, Special Topic, Marine Seismic, vol. 29, Dec. 2011.

N. Moldoveanu et al., "What is the next step after WAZ for exploration in the Gulf of Mexico?", SEG International Exposition and Annual Meeting, Houston, Texas, Oct. 23-29, 2009, pp. 41-45.

J. Naranjo et al., "Survey Design and Implementation of a Multiple Wide-Azimuth Towed Streamer Seismic Acquisition Strategy at the Tiber Discovery; Deep Water Gulf of Mexico, USA", SEG Annual Meeting, San Antonio, Texas, Sep. 18-23, 2011, pp. 132-136.

\* cited by examiner

Figure 1(b)  
(Background Art)

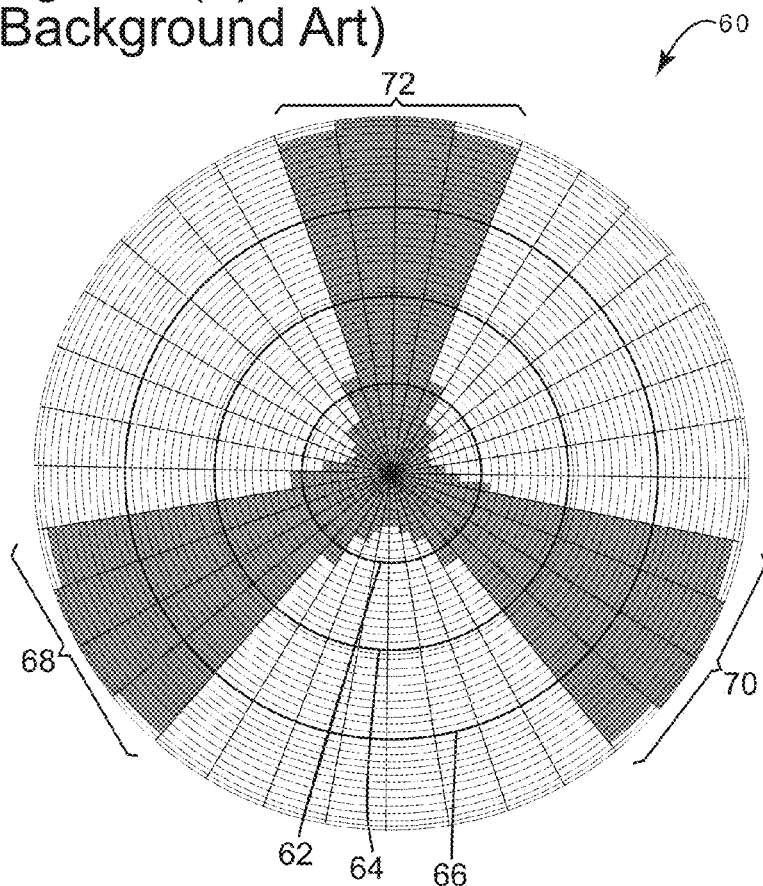


Figure 1(c)  
(Background Art)

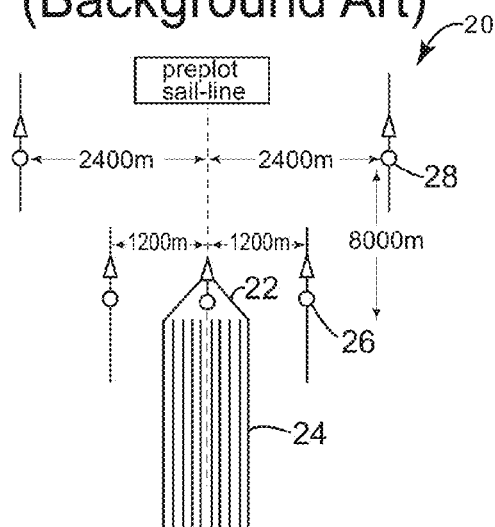


Figure 1(d)  
(Background Art)

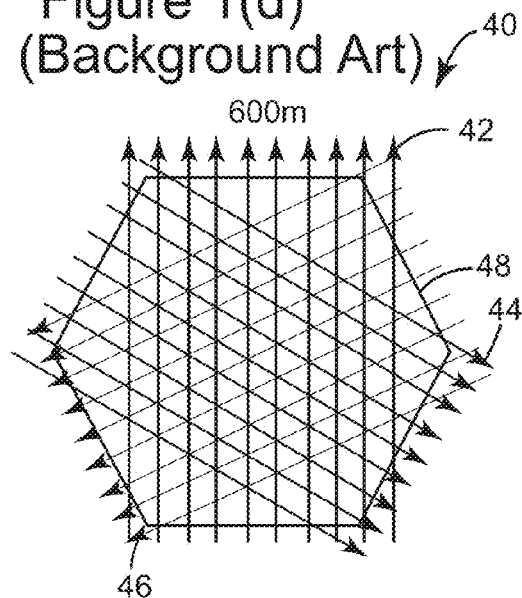


Figure 2

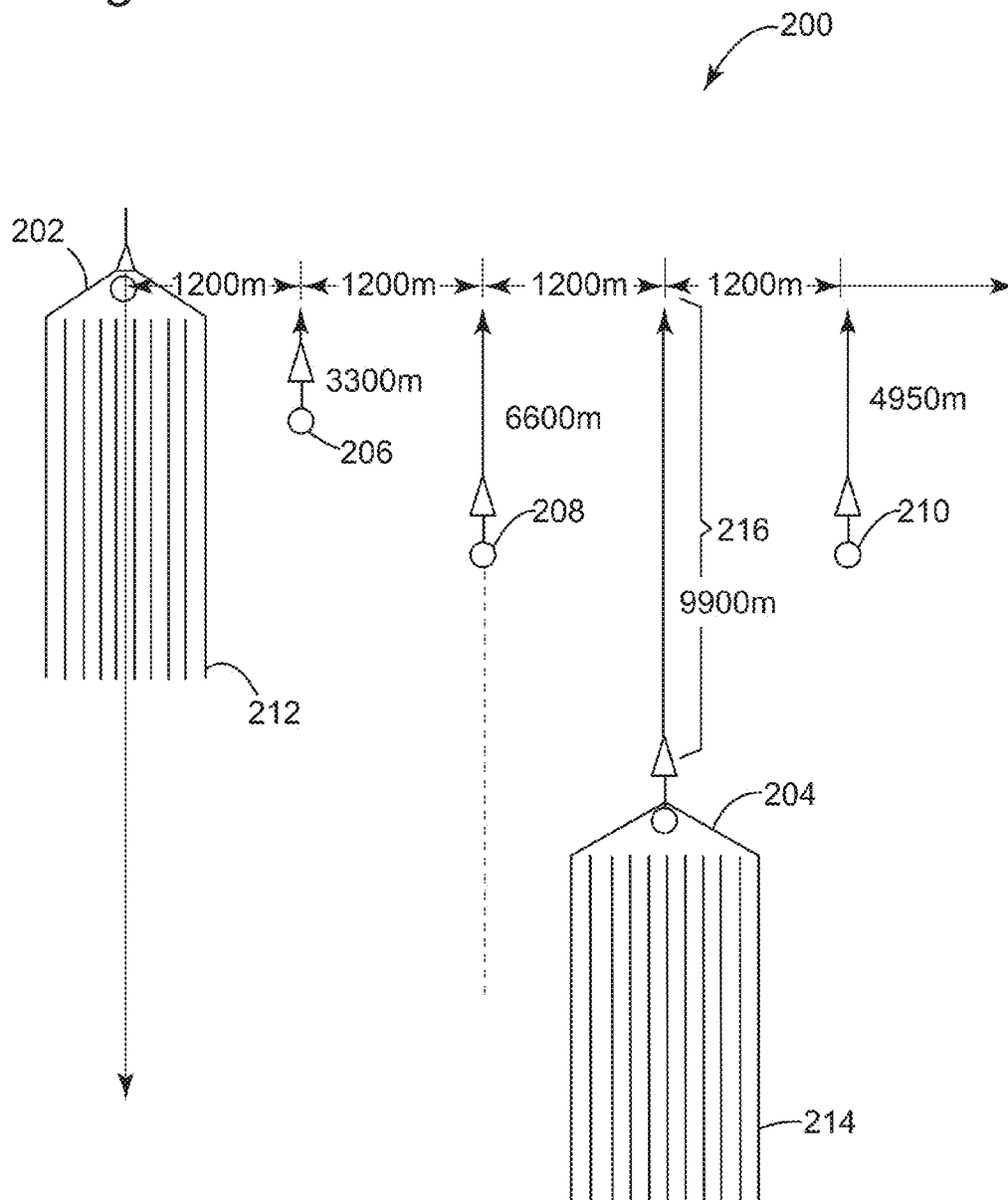
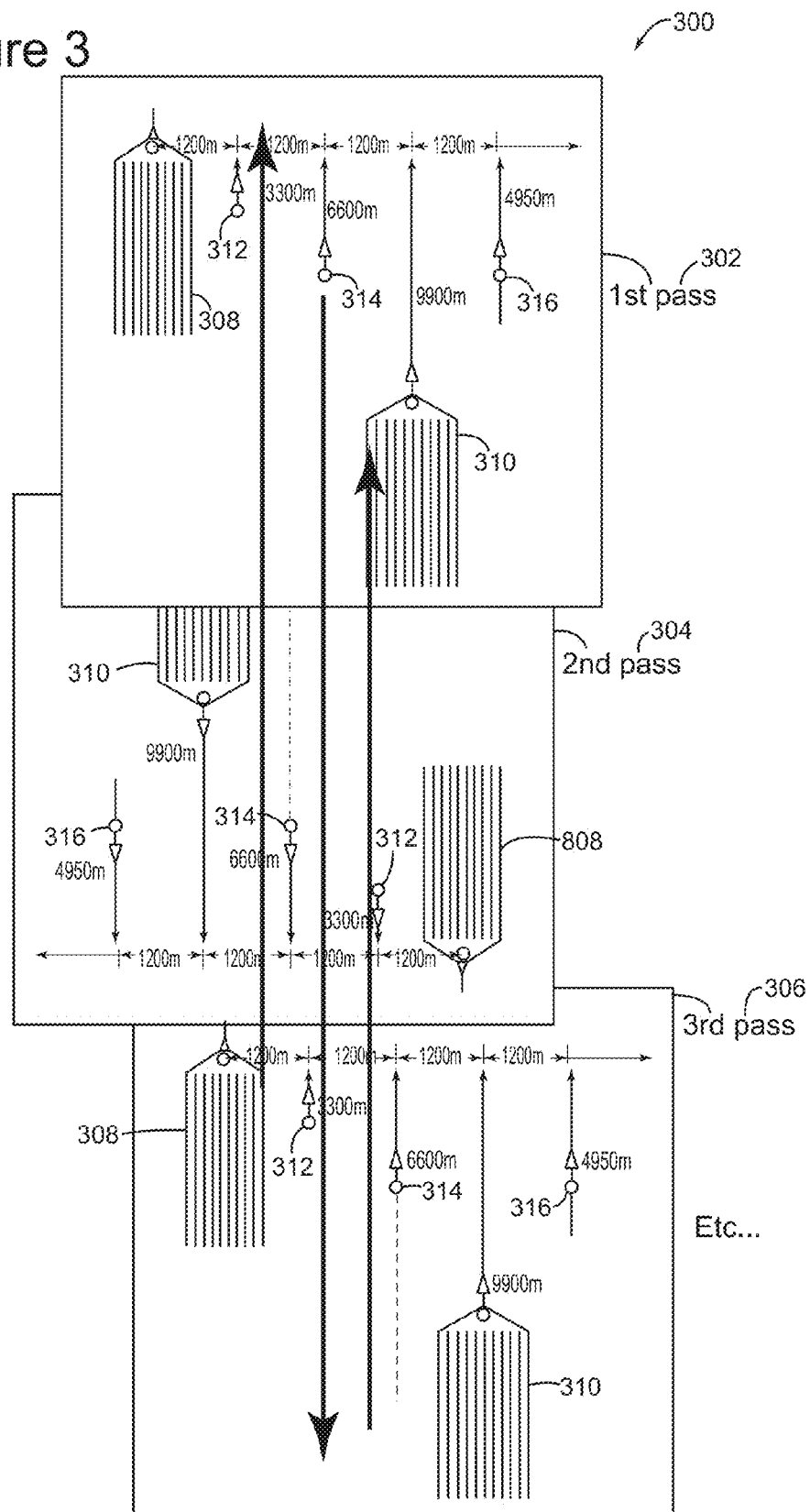


Figure 3



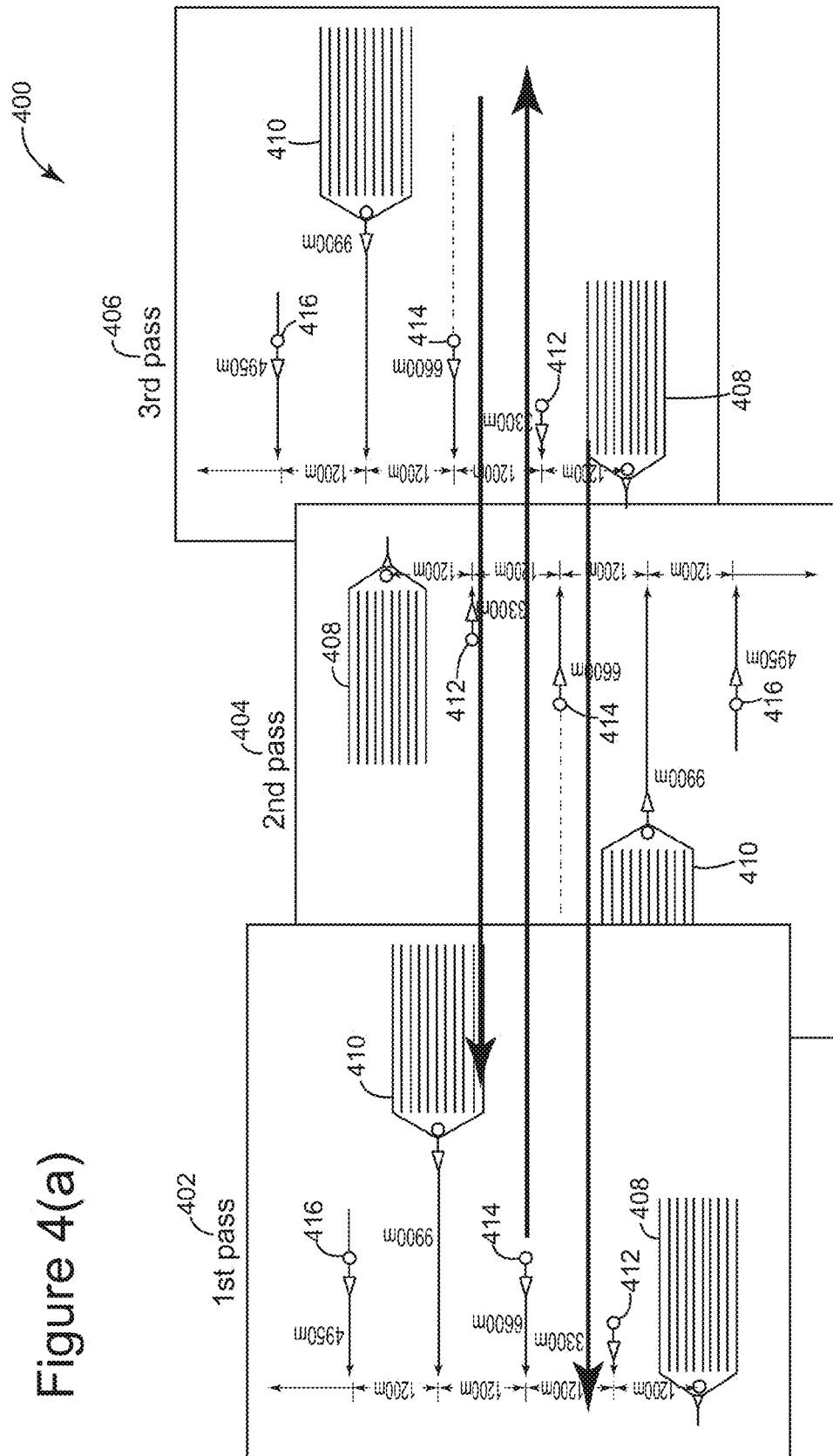


Figure 4(b)

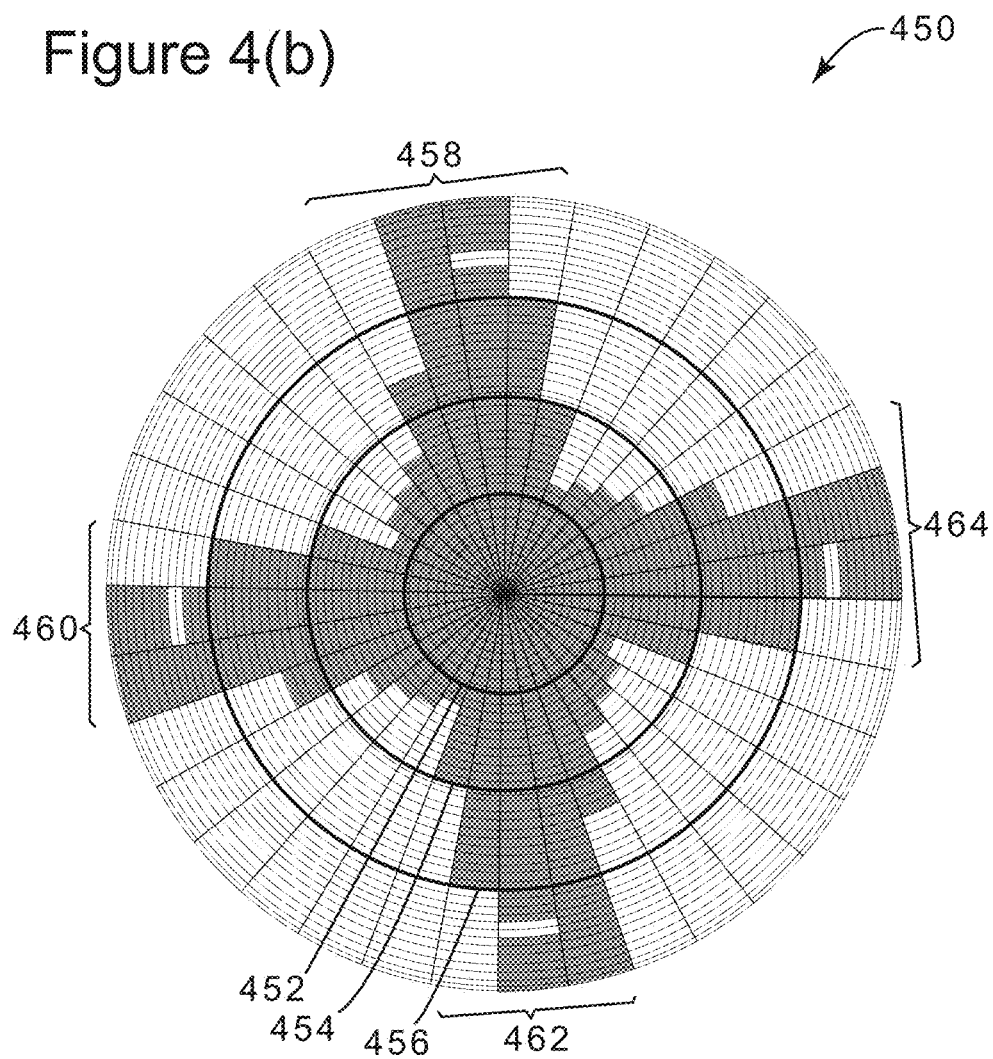
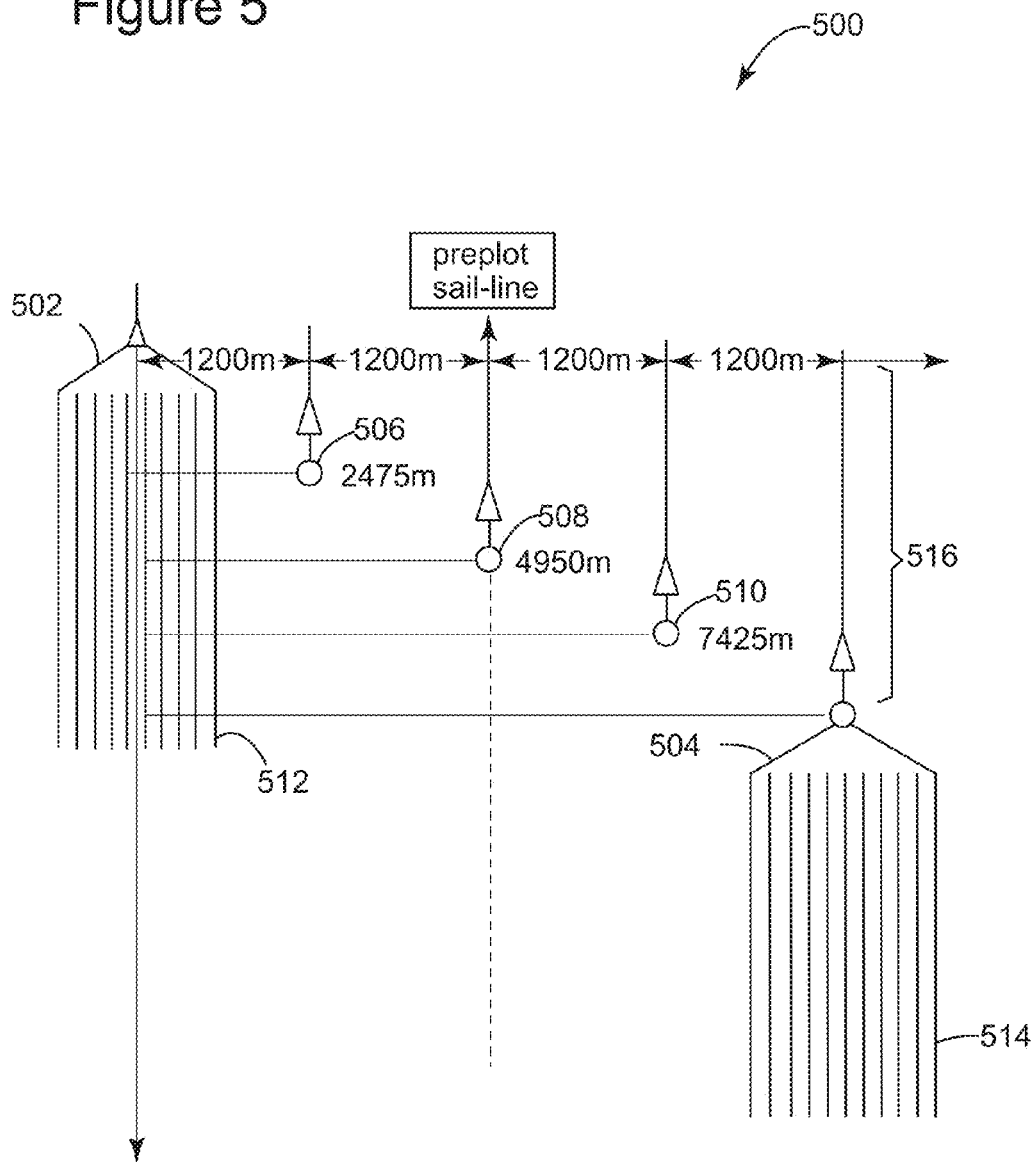


Figure 5





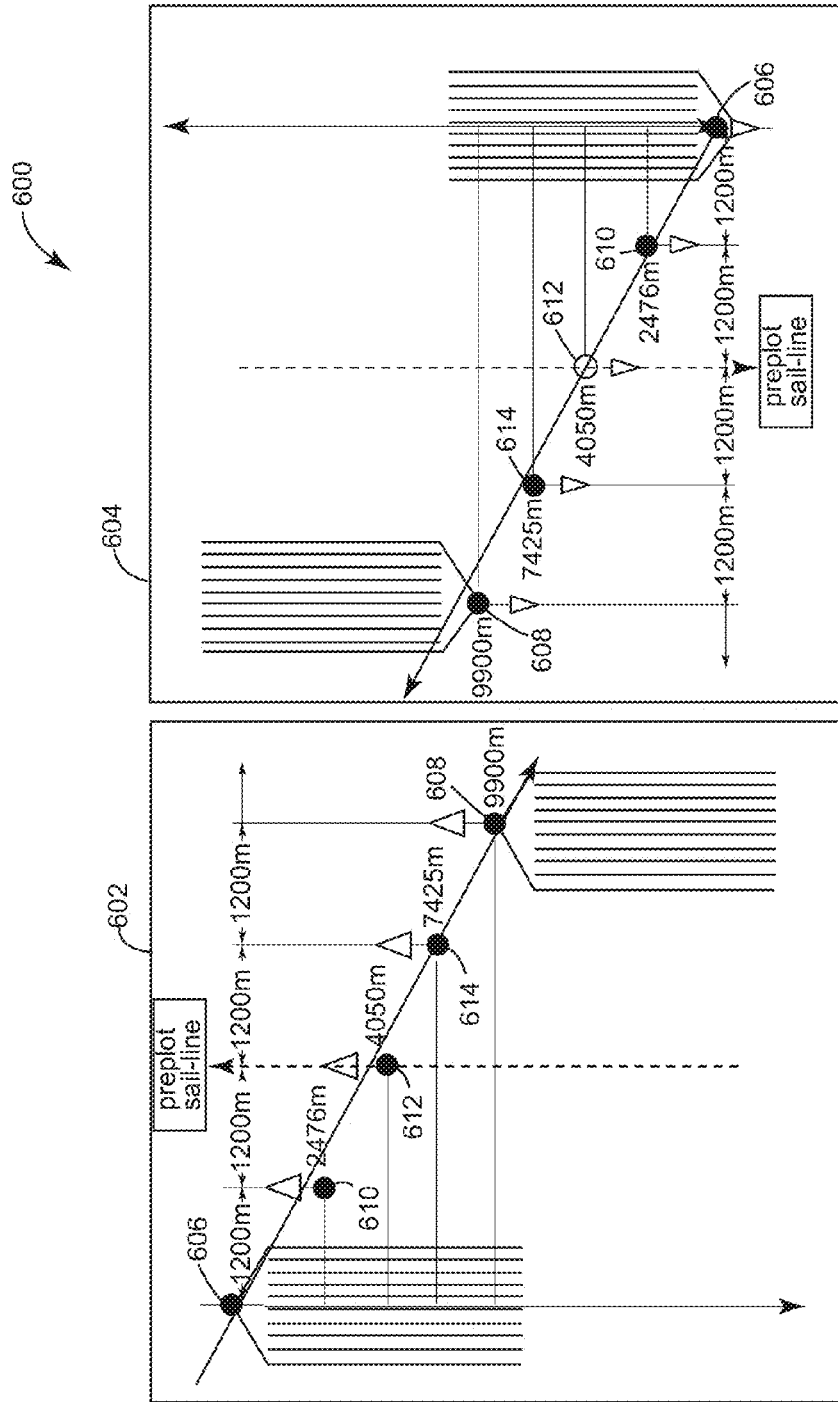


Figure 6

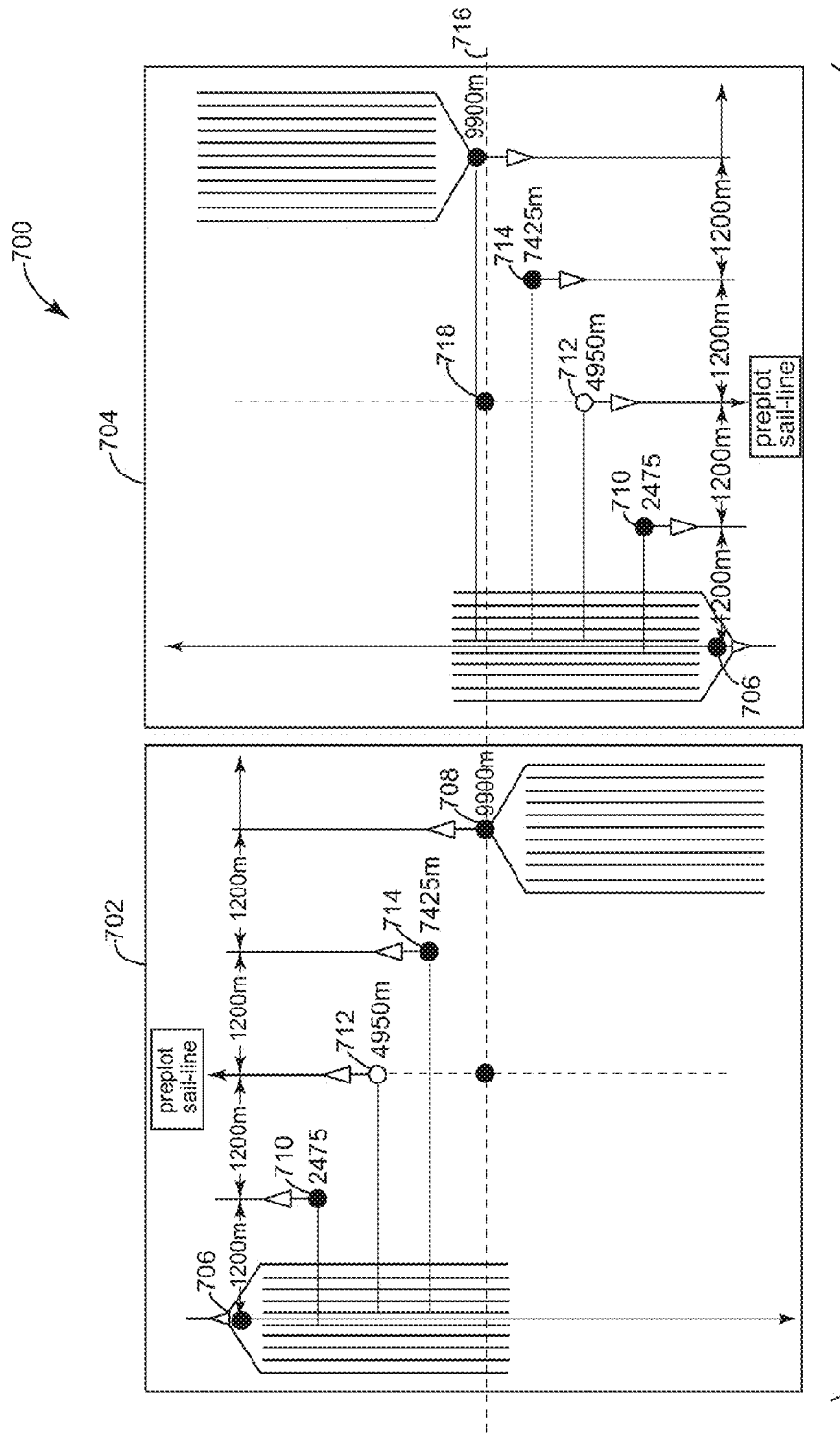


Figure 7(a)

Figure 7(b)

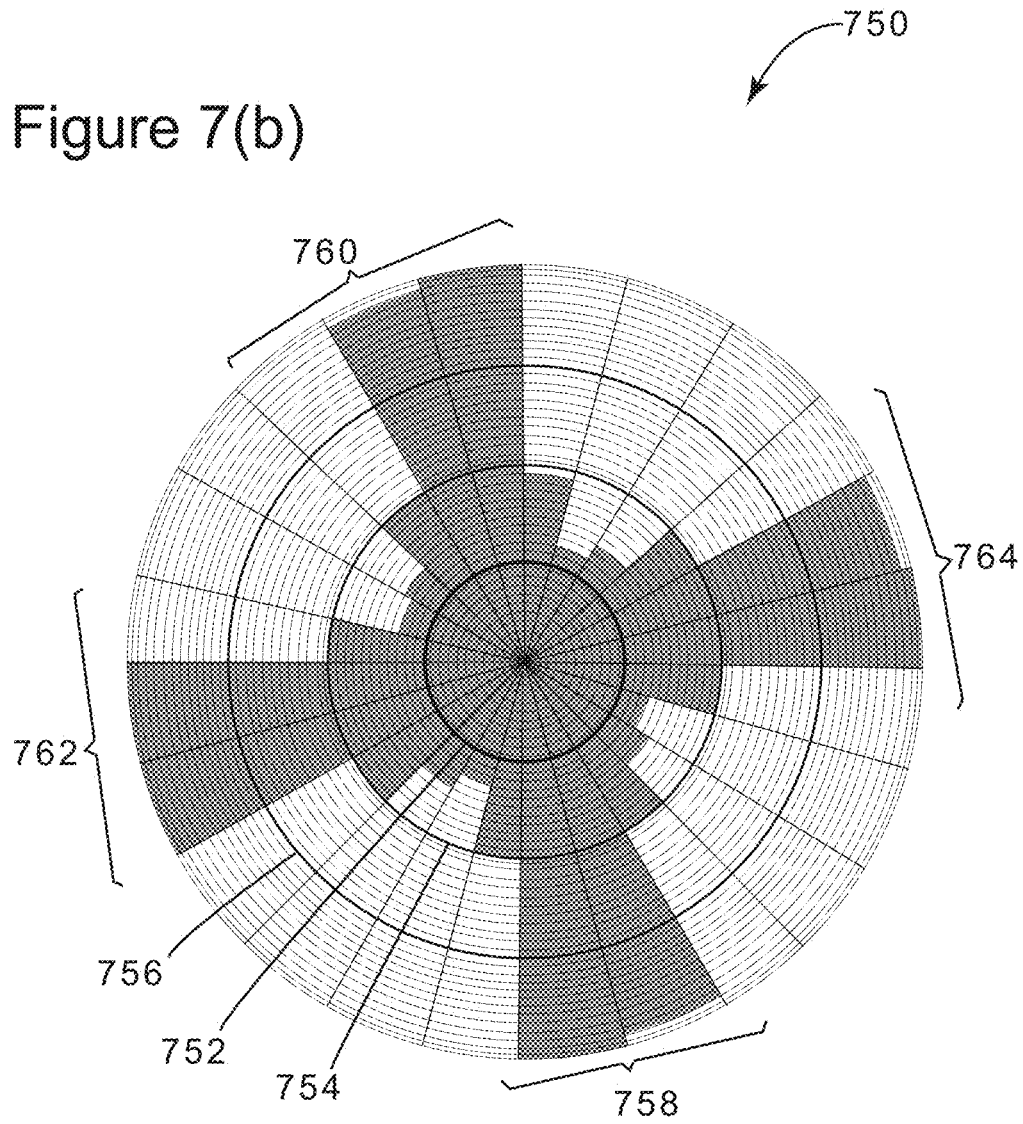


Figure 7(c)

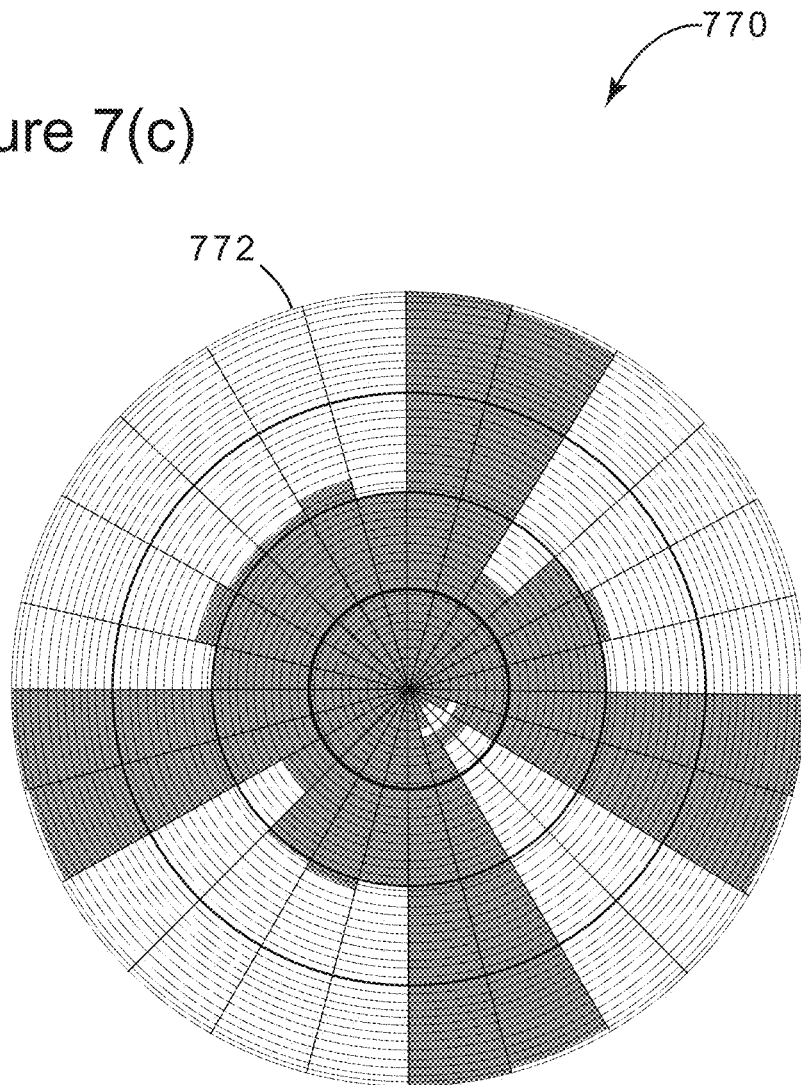


Figure 7(d)

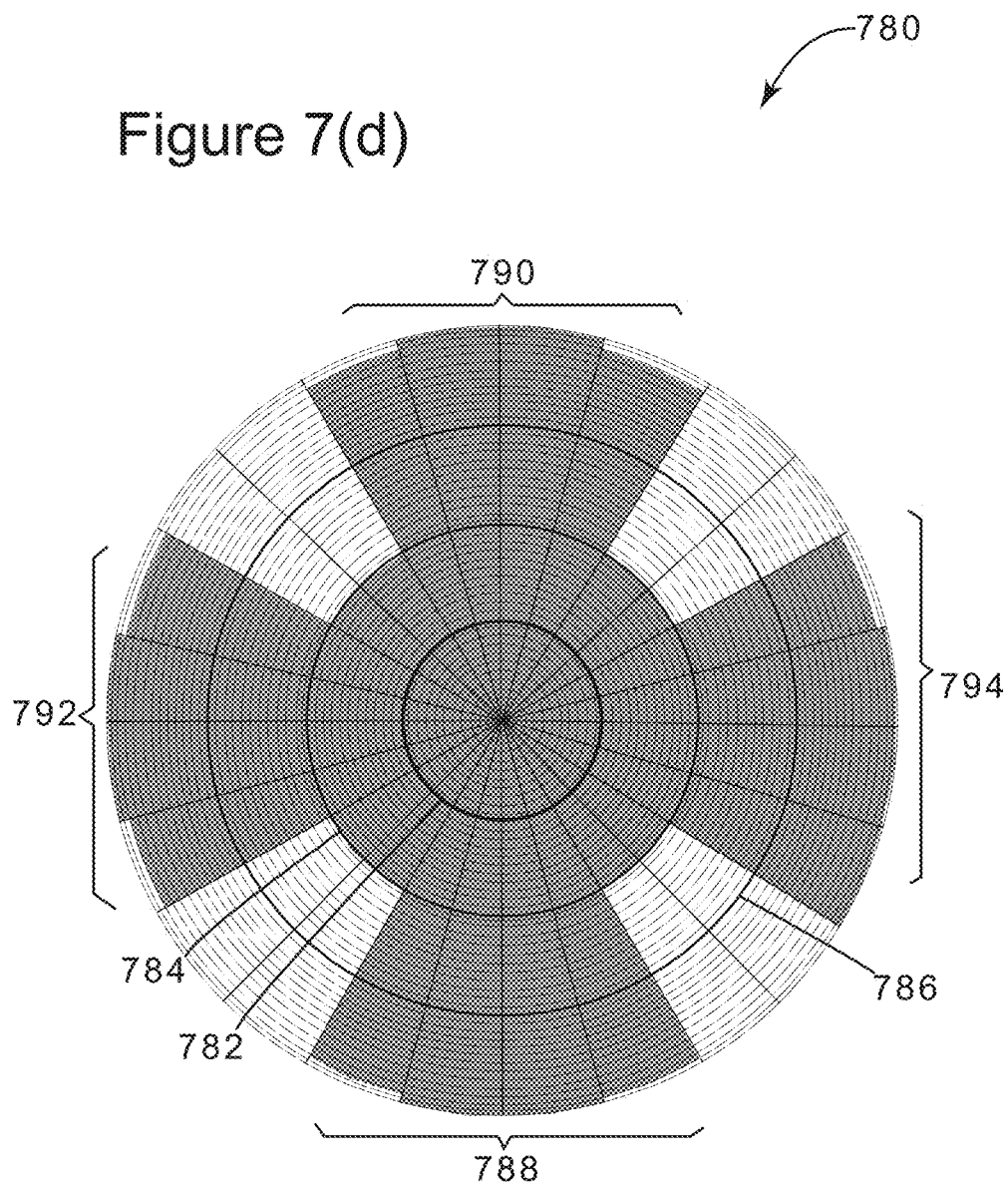


Figure 8

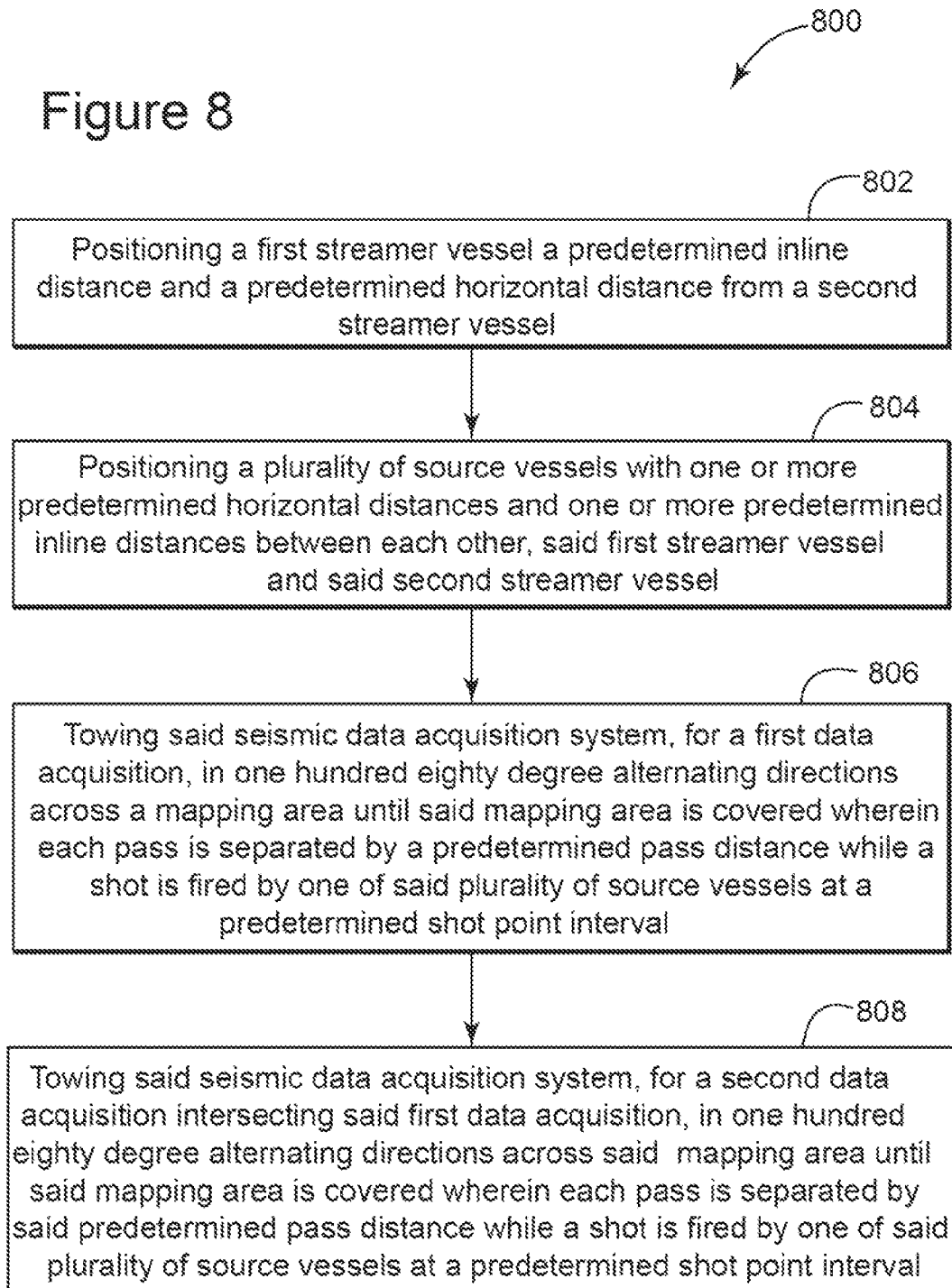
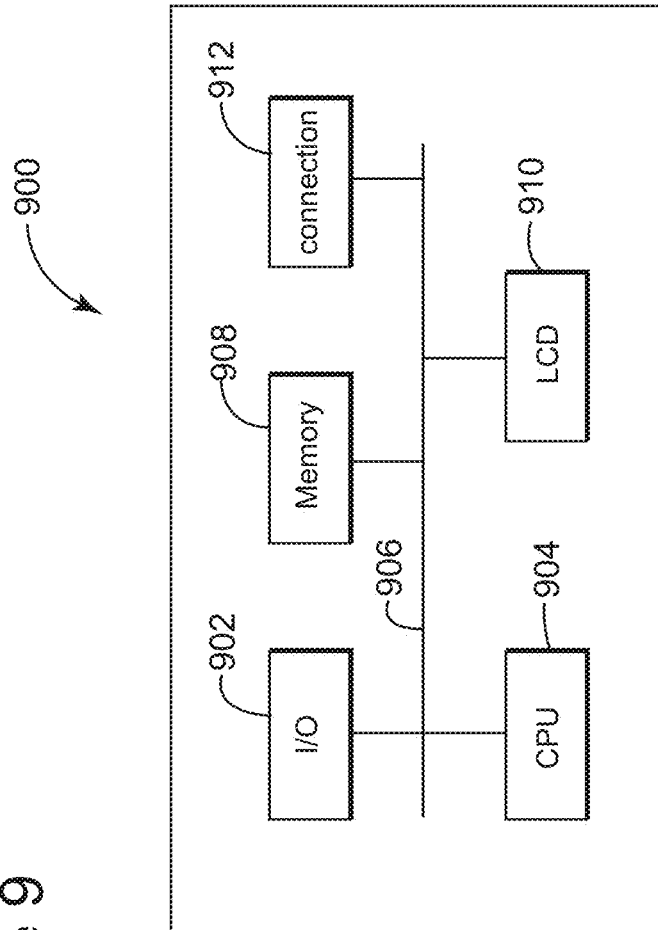


Figure 9



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## METHOD AND DEVICE FOR MARINE SEISMIC ACQUISITION

### RELATED APPLICATION

The present application is related to, and claims priority from U.S. Provisional Patent Application No. 61/582,633, filed Jan. 3, 2012, entitled "STAGSEIS," to Fabrice Mandroux, the disclosure of which is incorporated herein by reference and U.S. Provisional Patent Application No. 61/587,285, filed Jan. 17, 2012, entitled "STAGSEIS," to Fabrice Mandroux, the disclosure of which is incorporated herein by reference.

### TECHNICAL FIELD

Embodiments of the subject matter disclosed herein generally relate to methods and systems for marine seismic data acquisition and, more particularly, to mechanisms and techniques for improved azimuth and offset distribution in marine seismic data acquisition.

### BACKGROUND

Marine seismic data acquisition and processing techniques are used to generate a profile (image) of a geophysical structure (subsurface) under the seafloor. This profile does not necessarily provide an accurate location for oil and gas reservoirs, but it may suggest, to those trained in the field, the presence or absence of oil and/or gas reservoirs. Thus, providing better image of the subsurface is an ongoing process.

For a seismic gathering process, as shown in FIG. 1(a), a data acquisition system 10 includes a vessel 12 towing plural streamers 14 that may extend over kilometers behind the vessel. One or more source arrays 16 may be also towed by the vessel 10 or another vessel for generating seismic waves. Conventionally, the source arrays 16 are placed in front of the streamers 14, considering a traveling direction of the vessel 10. The seismic waves generated by the source arrays propagate downward and penetrate the seafloor, eventually being reflected by a reflecting structure (not shown) back to the surface. The reflected seismic waves propagate upwardly and are detected by detectors provided on the streamers 14. This process is generally referred to as "shooting" a particular seafloor area, which area is referred to as a "cell". However, such a method results in data having poor azimuth distribution.

An improvement to this conventional data acquisition method is the use of wide-azimuth (WAZ) acquisition. In a typical WAZ survey, two streamer vessels and multiple sources are used to cover a large sea area, and all sources and streamers are controlled at a uniform depth throughout the survey. WAZ acquisition provides better illumination of the substructure and, thus, a better final image.

A newer approach, rich-azimuth (RAZ) acquisition, shows promising signs for improving the final image. RAZ acquisition is the combination of multi-azimuth acquisition and wide-azimuth geometry. RAZ acquisition may be implemented by shooting a same cell in three directions, e.g., 30°, 90°, and 150°, each direction being shot in one or two passes. A rose diagram (an example of which will be described below with respect to FIG. 1(b)) for such a rich-azimuth survey shows the benefits of rich-azimuth towed-streamer acquisition.

A seismic data acquisition system 20, shown in FIG. 1(c) depicts a plurality of streamers 24 attached to a streamer vessel 22 which can be used to perform seismic surveys. The

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streamer vessel bisects two pairs of source vessels 26, 28 with the first pair of source vessels 26 configured 1200 meters cross-line on each side of the streamer vessel 22 and the second pair of source vessels 28 configured 2400 meters cross-line on each side of the streamer vessel 22. It should be noted that the first pair of source vessels 26 are in-line with the streamer vessel 22 and the second pair of source vessels 28 are 8000 meters in-line in front of the streamer vessel 22.

Looking now to FIG. 1(d), a honeycomb pattern 40 for towing the seismic data acquisition system 20 is depicted. The honeycomb pattern 40 is created by towing the prior art seismic data acquisition system 20 in three intersecting directions 42, 44, 46 across the mapping area 48. For the configuration of the seismic data acquisition system 20, the passes across the mapping area 48 in the same direction are separated by 600 meters. It should be noted that the three towing directions 42, 44, 46 are each rotated one hundred twenty degrees from each other and each towing direction does not use an antiparallel acquisition towing pattern. Further, shots are fired, based on a predetermined shot point interval, as the seismic data acquisition system 20 is towed across the mapping area.

Looking now to FIG. 1(b), a Rose diagram 60 of the data collected by the prior art seismic data acquisition system 20 is depicted. The Rose diagram illustrates a 5000 meter distance 62, a 10,000 meter distance 64 and a 15,000 meter distance 66. Continuing with the Rose diagram 60, three azimuthal bands 68, 70, 72 of charted data are shown representing the three towing directions of the seismic data acquisition system 20. Blank regions indicate areas where no data was collected as a result of the seismic data system 20 configuration, tow patterns 42, 44, 46 and the shot point interval. Consequently, it can be seen from the Rose diagram 60 that none of the concentric rings 62, 64, 66 representing a mapping area have complete coverage with collected seismic data.

However, the existing RAZ acquisition techniques can further be improved to increase the illumination and accuracy of the final image by finding an appropriate number and distribution of source arrays and streamer vessels to achieve ultra-long offset together with broadband techniques. Accordingly, it would be desirable to provide systems and methods that avoid the afore-described problems and drawbacks, and improve the accuracy of the final image.

### SUMMARY

According to an exemplary embodiment, a survey acquisition system includes a plurality of streamers towed by a plurality of streamer vessels, including a first streamer vessel and a second streamer vessel and a plurality of sources towed by a plurality of source vessels. The plurality of streamer vessels and plurality of source vessels are configured relative to one another such that the plurality of source vessels are positioned at one or more predetermined inline distances behind a portion of the first streamer vessel and are also positioned at one or more predetermined inline distances in front of a portion of the second streamer vessel. The plurality of streamer vessels and plurality of source vessels are also spaced apart from one another in a cross-line direction.

According to another exemplary embodiment, a method for seismic data acquisition, includes configuring a seismic data acquisition system by: positioning a plurality of source vessels at one or more predetermined inline distances behind a portion of a first streamer vessel, positioning the plurality of source vessels at one or more predetermined inline distances in front of a portion of a second streamer vessel, and spacing the plurality of streamer vessels and the plurality of source vessels apart from one another in a cross-line direction; and



acquiring the seismic data using the configured seismic data acquisition system by shooting sources associated with the plurality of source vessels to generate acoustic signals and receiving reflected acoustic signals at streamers associated with the first streamer vessel and the second streamer vessel.

### BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate one or more embodiments and, together with the description, explain these embodiments. In the drawings:

FIGS. 1(a)-1(d) are various illustrations associated with background art seismic data acquisition systems;

FIG. 2 is a schematic diagram of a novel seismic data acquisition system according to an exemplary embodiment wherein all source vessels are not located cross-line between streamer vessels;

FIG. 3 is a schematic diagram of a novel seismic data acquisition system according to an exemplary embodiment wherein different passes in an in-line direction are depicted;

FIG. 4(a) is a schematic diagram of a novel seismic data acquisition system according to an exemplary embodiment wherein different passes in a cross-line direction are depicted;

FIG. 4(b) is an exemplary embodiment of a rose diagram associated with a novel seismic data acquisition system;

FIG. 5 is a schematic diagram of a seismic data acquisition system having plural source vessels located cross-line between streamer vessels according to an exemplary embodiment;

FIG. 6 is a schematic diagram of a seismic data acquisition system having plural source vessels wherein streamer vessels maintain relative position during adjacent passes;

FIG. 7(a) is a schematic diagram of a seismic data acquisition system having plural source vessels wherein streamer vessels change relative position during adjacent passes;

FIG. 7(b) is an exemplary embodiment of a rose diagram associated with a novel seismic data acquisition system wherein streamer vessels maintain relative position during adjacent passes;

FIG. 7(c) is an exemplary embodiment of a rose diagram associated with a novel seismic data acquisition system wherein streamer vessels do not maintain relative position during adjacent passes;

FIG. 7(d) is an exemplary embodiment of a rose diagram associated with a novel seismic data acquisition system wherein streamer vessels do not maintain relative position during adjacent passes and reciprocity of data is applied;

FIG. 8 is a flowchart illustrating a method for collecting seismic data with an exemplary embodiment of a novel seismic data acquisition system; and

FIG. 9 is a schematic diagram of a computerized system that implements various methods according to an exemplary embodiment.

### DETAILED DESCRIPTION

The following description of the exemplary embodiments refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. The following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims. Some of the following embodiments are discussed, for simplicity, with regard to the terminology and structure of RAZ acquisition using one or more streamer vessels and a plurality of sources. However, the embodiments

to be discussed next are not limited to these configurations, but may be extended to other arrangements as discussed later.

Reference throughout the specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with an embodiment is included in at least one embodiment of the subject matter disclosed. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” in various places throughout the specification is not necessarily referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

In order to provide a context for the subsequent exemplary embodiments, a description of aspects and terminology is hereby included. It should be noted in an exemplary embodiment that an individual source can be, for example, an air gun. In another aspect of an exemplary embodiment, objects named birds can be located on the one or more lines connected to the one or more streamer vessels for maintaining the streamers in the desired positions. Continuing with an exemplary embodiment, the birds are devices capable of maintaining a cross-line position or a depth position. In another aspect of an exemplary embodiment, a coordinate system for describing the direction of travel of the different vessels can be related to an X-axis, Y-axis system wherein the X-axis is the direction of travel of the vessels or in-line direction and the Y-axis, also known as the cross-line direction, is perpendicular to the X-axis direction.

Continuing with the general context description of an exemplary embodiment, the individual sources can be fired based on various schemes. One scheme in an exemplary embodiment can shoot the sources sequentially. For example, fire the sources at 37.5 meter intervals, i.e., shoot a first front source, wait for the first source to travel 37.5 meters along the X-axis, then shoot the central source and so on. It should be noted in the exemplary embodiment that the value of 37.5 meters is an example and can vary, e.g., based on the speed of the streamer vessel. In this fashion, the sources are fired when, for example, they have the same X-axis, or in-line, position during a firing sequence.

It should further be noted in the exemplary embodiment that a firing sequence includes the sequential one-time firing of each source. In another exemplary embodiment firing sequence, the sources are fired either simultaneously or almost simultaneously with random time delays between firings. It should be noted in the exemplary embodiment that for a twenty kilometer offset the tail sources must be shot until the end of the full-fold boundary. Further, it should be noted in an exemplary embodiment that a large offset between a source and a traveling distance is considered by the industry to be equal to or larger than two thousand meters.

According to an exemplary embodiment, a system configuration for enriching RAZ acquisition includes plural streamer vessels configured to tow plural streamers and plural source vessels configured to tow one or more source arrays. For example, three source vessels may be configured to sail parallel to two streamer vessels. The three source vessels may be positioned between the two streamer vessels in a traveling (inline) direction and, according to an embodiment, also in a cross-line direction.

For example, in the following embodiments two streamer vessels can be arranged in a staggered relationship relative to each other to provide a stretching of the vessel setup or configuration in both the inline and cross-line directions. More specifically, according to some embodiments, a five vessel setup or configuration can be specified by placing vessels at the following relative coordinates:

## 5

One streamer vessel is positioned at coordinate (0,0),  
One source vessel at approximately coordinate (SW;−SL/  
3),

One source vessel at approximately coordinate (SW\*2;−  
2\*SL/3),

One streamer vessel at approximately coordinate (SW\*3;−  
SL), and

One source vessel at approximately coordinate (SW\*4;−  
SL/2), where

The coordinate variables are determined as follows:

NS=number of streamers per vessel, SP=separation  
between streamers.

SW=NS\*SP,

SPI=Shot point interval, and

SL=streamer length adjusted so that SL is a multiple of  
SPI, 2 and 3. For example, if the nominal streamer length  
is 10000 m and SPI=37.5 m, then SL=9900 m.

In operation, the acquisition of seismic data from a cell  
using the above-described vessel configuration can be  
achieved by performing consecutive passes of the vessel con-  
figuration over the cell with each pass being separated by a  
distance of SW/2 and with each source vessel shooting alter-  
nately with an inline distance defined by SPI. Additionally, as  
will be discussed in more detail below with respect to FIG. 8,  
according to an embodiment, alternative configurations can  
be used in each successive (opposite) pass to perform inter-  
leaved acquisition.

To better understand how a streamer/source vessel con-  
figuration according to these embodiments can be established  
using the above-described locational relationships between  
the vessels, an exemplary embodiment of seismic towed ves-  
sels **200** is depicted in FIG. 2. In this purely illustrative  
example, the variable configuration values described above  
have been selected to be NS=10, SP=120, SW=1200,  
SPI=37.5 m, and SL=9900 m and, therefore applying the  
relationships described above, a first streamer vessel **202** is  
disposed at coordinates (0,0), a first source vessel **206** is  
disposed at coordinates (1200 m,−3300 m), a second source  
vessel **208** is disposed at (2400 m,−6600 m), a second  
streamer vessel **204** is disposed at coordinates (3600 m,−9900  
m), and a third source vessel is disposed at coordinates (4800  
m,−4950 m).

It should be noted in the exemplary embodiment that the  
seismic towed streamer vessels **202**, **204** are configurable  
with respect to the number of streamers **212**, **214** per vessel,  
the separation (offset) distance between the streamer vessel  
**702** and streamer vessel **704** and the length of the streamers  
**212**, **214**. Further, it should be noted in the exemplary  
embodiment that the streamer vessels **202**, **204** are separated  
(offset) in the cross-line direction by one or more source  
vessels **206**, **208** and the leading edge of the streamer vessels  
**202**, **204** are offset in the in-line direction from each other by  
a predefined distance **216**. Further, it should be noted in the  
exemplary embodiments that the streamer vessels can overlap  
in the in-line direction and the streamers associated with a  
given streamer vessel can have variable distances between the  
streamers.

As implied by the coordinates at which the vessels are  
placed and as shown in FIG. 2, the in-line and cross-line  
offsets of the vessels relative to one another can be described  
as follows. The streamer vessel **202** is adjacent to source  
vessel **206** wherein source vessel **206** is cross-line offset by  
one thousand two hundred meters from streamer vessel **202**  
and in-line offset by three thousand three hundred meters  
from the leading edge of streamer vessel **202**. Source vessel  
**206** is adjacent to source vessel **208** wherein source vessel  
**208** is cross-line offset by two thousand four hundred meters

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from streamer vessel **202** and in-line offset by six thousand  
six hundred meters from the leading edge of streamer vessel  
**202**. Source vessel **208** is adjacent to streamer vessel **204**  
wherein streamer vessel **204** is cross-line offset by three thou-  
sand six hundred meters from streamer vessel **202** and in-line  
offset by nine thousand nine hundred meters from the leading  
edge of streamer vessel **202**. Streamer vessel **204** is adjacent  
to source vessel **210** wherein source vessel **210** is cross-line  
offset by four thousand eight hundred meters from streamer  
vessel **202** and in-line offset by four thousand nine hundred  
fifty meters from the leading edge of streamer vessel **202**. It  
should be noted in the exemplary embodiment of FIG. 2 that  
each streamer vessel and source vessel can be attached to  
independent tow lines connected to a tow vessel. As men-  
tioned earlier, the specific offset distances described above  
and shown in FIG. 2 are purely illustrative of one exemplary  
configuration and those skilled in the art will appreciate that  
other embodiments can use other offset distances.

Continuing with the exemplary embodiment, acquisition  
geometry is defined by making consecutive passes over the  
mapping area (cell) with each pass separated by a distance of  
one-half of the streamer width and each source vessel shoot-  
ing alternatively with an inline distance defined shot point  
interval. It should be noted that each alternative can be per-  
formed in an opposite pass, i.e., interleave acquisition. It  
should further be noted that to achieve a wide azimuth distri-  
bution, the same setup can be repeated in one or more direc-  
tions, i.e., multiple passes can be executed at an angle to the  
direction of the previous passes.

Looking now to FIG. 3, an exemplary embodiment of an  
antiparallel acquisition pattern **300** using the vessel configu-  
ration of FIG. 2 is depicted. The exemplary embodiment  
antiparallel acquisition pattern **300** comprises a first pass **302**,  
a second pass **304**, a third pass **306**, a streamer vessel **308**, a  
streamer vessel **310** and source vessels **312**, **314**, **316**. It  
should be noted in the exemplary embodiment that other  
configurations can have a different number of streamer ves-  
sels and/or source vessels. Further, it should be noted in the  
exemplary embodiment that the first pass **302** and the third  
pass **306** travel in the same direction, a direction approxi-  
mately one hundred eighty degrees rotated from the direction  
of travel of the second pass **304** and the distance between pass  
centerlines is approximately one half of the streamer vessel  
width (SW/2) on each pass.

Looking now to FIG. 4(a), another exemplary embodiment  
antiparallel acquisition pattern **400** is depicted. The exem-  
plary embodiment antiparallel acquisition pattern **400** com-  
prises a first pass **402**, a second pass **404**, a third pass **406**, a  
streamer vessel **408**, a streamer vessel **410** and source vessels  
**412**, **414**, **416**. It should be noted in the exemplary embodi-  
ment that although the antiparallel acquisition pattern **400**  
resembles the antiparallel acquisition pattern **300**, the anti-  
parallel acquisition pattern **400** traverses a direction perpen-  
dicular to and crossing the path traveled by antiparallel acqui-  
sition pattern **300**. Further, it should be noted in the exemplary  
embodiment that the first pass **402** and the third pass **406**  
travel in the same direction, a direction approximately one  
hundred eighty degrees rotated from the direction of travel of  
the second pass **404** and the distance between pass centerlines  
is approximately one half of the streamer vessel width (SW/2)  
on each pass.

Looking now to FIG. 4(b), another Rose diagram **450** of the  
data collected by the exemplary embodiment seismic data  
acquisition system **200** is depicted. The exemplary embodi-  
ment Rose diagram **450** illustrates a 5000 meter distance **452**,  
a 10,000 meter distance **454** and a 15,000 meter distance **456**  
of a circular area. Continuing with the exemplary embodi-

ment Rose diagram **450**, four azimuthal bands **458**, **460**, **462**, **464** of charted data are shown representing the two antiparallel towing directions of the seismic data acquisition system **200**. Blank regions indicate areas where no data was collected as a result of the seismic data system **200** configuration, antiparallel tow patterns and the shot point interval. Accordingly, it can be seen from the Rose diagram **450** that coverage area of the seismic data is an improvement over the coverage area represented by Rose diagram **60** wherein the 5000 meter concentric ring **452** having complete coverage.

According to other embodiments, a different streamer vessel/source configuration than those described above with respect to FIGS. 1-2 can be used to perform marine seismic surveys. In the following embodiments, instead of a single streamer vessel as in the foregoing embodiments, two streamer vessels can be arranged in a staggered relationship relative to each other to provide a stretching of the vessel setup or configuration in both the inline and cross-line directions. More specifically, according to some embodiments, a five vessel setup or configuration can be specified by placing vessels at the following relative coordinates:

One streamer vessel is positioned at coordinate (0, 0),

One source vessel at approximately coordinate (SW; -SL/4),

One source vessel at approximately coordinate (SW\*2; -2\*SL/4),

One streamer vessel at approximately coordinate (SW\*3; 3\*SL/4), and

One source vessel at approximately coordinate (SW\*4; -SL), where the coordinate variables are determined as follows:

NS=number of streamers per vessel, SP=separation between streamers.

SW=NS\*SP,

SPI=Shot point interval, and

SL=streamer length adjusted so SL is a multiple of SPI and 2. For example, if the nominal streamer length is 10000 meters and SPI=37.5 meters, then SL=9900 meters.

In operation, the acquisition of seismic data from a cell using the above-described vessel configuration can be achieved by performing consecutive passes of the vessel configuration over the cell with each pass being separated by a distance of SW/2 and with each source vessel shooting alternately with an inline distance defined by SPI. Additionally, as will be discussed in more detail below with respect to FIG. 5, according to an embodiment, alternative configurations can be used in each successive (opposite) pass to perform interleaved acquisition.

Looking now to FIG. 5, another exemplary embodiment of seismic towed vessels **500** is depicted having a different vessel configuration than those described above. The exemplary embodiment of FIG. 5 comprises two seismic towed streamer vessels **502**, **504** and three seismic towed source vessels **506**, **508**, **510**. It should be noted in the exemplary embodiment that the seismic towed streamer vessels **502**, **504** are configurable with respect to the number of streamers **514**, **516** per vessel, the separation distance between streamer vessel **502** and streamer vessel **504** and the length of the streamers **514**, **516**. Further, it should be noted in the exemplary embodiment that the streamer vessels **502**, **504** are separated cross-line by one or more source vessels **506**, **508**, **510** and the leading edge of the streamer vessels **502**, **504** are in-line offset from each other by a configurable distance **516**. Further in the exemplary embodiment, the source vessels **506**, **508**, **510** are in-line offset from the streamer vessels **502**, **504** and from each other by a configurable in-line distance.

For example, streamer vessel **502** is adjacent to source vessel **506** wherein source vessel **506** is cross-line offset twelve hundred meters from streamer vessel **502** and in-line offset two thousand four hundred seventy-five meters from the leading edge of streamer vessel **502**, source vessel **506** is adjacent to source vessel **508** wherein source vessel **508** is cross-line offset two thousand four hundred meters from streamer vessel **502** and in-line offset four thousand nine hundred fifty meters from the leading edge of streamer vessel **502**, source vessel **508** is adjacent to source vessel **510** wherein source vessel **510** is cross-line offset three thousand six hundred meters from streamer vessel **502** and in-line offset seven thousand four hundred twenty-five meters from the leading edge of streamer vessel **502** and source vessel **510** is adjacent to streamer vessel **504** wherein streamer vessel **504** is cross-line offset four thousand eight hundred meters from streamer vessel **502** and in-line offset nine thousand nine hundred meters from the leading edge of streamer vessel **502**. It should be noted in the exemplary embodiment that each streamer vessel and source vessel can be attached to independent tow lines connected to a tow vessel.

Looking now to FIG. 6, an exemplary embodiment of an antiparallel acquisition pattern **600** is depicted. The exemplary embodiment antiparallel acquisition pattern **600** comprises a first pass **602**, a second pass **604**, a streamer vessel **606**, a streamer vessel **608** and source vessels **610**, **612**, **614**. It should be noted in the exemplary embodiment that other configurations can have a different number of streamer vessels and/or source vessels. Further, it should be noted in the exemplary embodiment that the first pass **602** and the second pass **604** travel in directions approximately one hundred eighty degrees rotated from each other and the distance between pass centerlines is approximately one half of the streamer vessel width (SW/2) on each pass. It should also be noted in the exemplary embodiment that additional passes can be made in conjunction with the size of the survey area.

Looking now to FIG. 7(b), another Rose diagram **750** of the data collected by the exemplary embodiment seismic data acquisition system **600** is depicted. The exemplary embodiment Rose diagram **750** illustrates a 5000 meter distance **752**, a 10,000 meter distance **754** and a 15,000 meter distance **756** of a circular area. Continuing with the exemplary embodiment Rose diagram **750**, four azimuthal bands **758**, **760**, **762**, **764** of charted data are shown representing the two antiparallel towing directions of the seismic data acquisition system **600**. Blank regions of the exemplary embodiment Rose diagram **750** indicate areas where no data was collected as a result of the seismic data system **600** configuration, antiparallel tow patterns and the shot point interval. Accordingly, it can be seen from the exemplary embodiment Rose diagram **750** that coverage area of the seismic data is an improvement over the coverage area represented by exemplary embodiment Rose diagram **450** wherein the 5,000 meter concentric ring **752** having complete coverage and the 10,000 meter concentric ring having near complete coverage.

According to another embodiment depicted in FIG. 7(a), the same vessel setup or configuration **602** used above with respect to FIG. 6 can be used to perform seismic acquisition, however according to this embodiment the setup is inverted **604** for each adjacent line or pass during the acquisition. The purpose of this setup is to take advantage of the reciprocity principle. The rose diagram **772** of data acquired with setup on FIG. 7a is shown FIG. 7(c). The rose diagram **772** illustrates an asymmetric data distribution. In this context, reciprocity implies that the seismic trace from point S(a) to R(b) is equivalent to the seismic trace from S(b) to R(a), where a and b are the locations of the source and receiver, reciprocally.

On a rose diagram (e.g., FIG. 7(d) discussed below), the reciprocal traces are disposed symmetrically with respect to the center. For embodiments which exploit this reciprocity principle, it is thus possible to provide more complete azimuth coverage in the rose diagram without doubling the fold.

An example of acquisition using reciprocity and vessel setup inversion according to an embodiment is provided as shown in FIG. 7(a). Therein, an exemplary embodiment antiparallel acquisition pattern **700** comprises a first pass **702**, a second pass **704**, a streamer vessel **706**, a streamer vessel **708** and source vessels **710**, **712**, **714** configured between streamer vessel **706** and streamer vessel **708**. It should be noted in the exemplary embodiment that other configurations can have a different number of streamer vessels and/or source vessels. Further, it should be noted in the exemplary embodiment that the first pass **702** and the second pass **704** travel in directions approximately one hundred eighty degrees rotated from each other and the distance between pass centerlines is approximately one half of the streamer vessel width (SW/2) on each pass. It should also be noted in the exemplary embodiment that additional passes can be made in conjunction with the size of the survey area. In another aspect of the exemplary embodiment, although alternating passes **702**, **704** are in directions approximately one hundred eighty degrees rotated from each other, the vessels are inverted with respect to each other such that they are rotated one hundred eighty degrees around an axis **716** perpendicular to the direction of travel rather than rotated one hundred eighty degrees in the plane of the vessels around a point **718** in the plane of the vessels.

Looking now to FIG. 7(c), another Rose diagram **770** of the data collected by the exemplary embodiment seismic data acquisition system **500** using the antiparallel tow pattern **700** is depicted. The exemplary embodiment Rose diagram **770** is inverted for each adjacent line or pass during the acquisition to take advantage of the reciprocity principle. The exemplary embodiment Rose diagram **780**, after reciprocity, illustrates a 5000 meter distance **782**, a 10,000 meter distance **784** and a 15,000 meter distance **786** of a circular area. Continuing with the exemplary embodiment Rose diagram **780**, four azimuthal bands **788**, **790**, **792**, **794** of charted data are shown representing the two antiparallel towing directions of the seismic data acquisition system **500** and implementing the reciprocity principle. Blank regions of the exemplary embodiment Rose diagram **780** indicate areas where no data was collected as a result of the seismic data system **500** configuration, antiparallel tow patterns and the shot point interval. Accordingly, it can be seen from the exemplary embodiment Rose diagram **780** that coverage area of the seismic data is a significant improvement over the coverage area represented by exemplary embodiment Rose diagram **750** wherein the 5,000 meter concentric ring **782** having complete coverage and the 10,000 meter concentric ring **784** also having complete coverage.

Looking now to FIG. 8, an exemplary method embodiment **800** for seismic data acquisition is depicted. Beginning at step **802**, the exemplary embodiment method configures a seismic data acquisition system by positioning a first streamer vessel a predetermined in-line distance and a predetermined cross-line distance from a second streamer vessel. It should be noted in the exemplary method embodiment the predetermined cross-line distance and the predetermined in-line distance can change between passes of the seismic data acquisition system over the sampled area.

Next, at step **804**, the exemplary embodiment method further configures a seismic data acquisition system by positioning a plurality of source vessels with one or more predeter-

mined cross-line distances and one or more predetermined in-line distances between each other, the first streamer vessel and the second streamer vessel. It should be noted in the exemplary method embodiment that the predetermined cross-line distances and the predetermined in-line distances can be different between pairs of vessels and between different passes of the seismic data acquisition system over the sampled area.

Next at step **806**, the exemplary method embodiment continues by towing the seismic data acquisition system, for a first data acquisition, in one hundred eighty degree alternating passes across a mapping area until the mapping area has been covered. Continuing with the exemplary method embodiment, each pass of the seismic data acquisition system is separated by a predetermined pass distance and a shot is fired by one of the plurality of source vessels at a predetermined shot point interval. It should be noted in the exemplary method embodiment that the pass distance and the shot point interval can vary between passes and between shots respectively.

Next at step **808**, the exemplary method embodiment continues by towing the seismic data acquisition system for a second data acquisition, intersecting the first data acquisition, in one hundred eighty degree alternating passes across the mapping area until the mapping area is covered. Continuing with the exemplary embodiment, each pass is separated by a predetermined pass distance and a shot is fired by one of said plurality of source vessels at a predetermined shot interval. It should be noted in the exemplary method embodiment that the pass distance and the shot point interval can vary between passes and between shots respectively.

One or more of the methods discussed above may be implemented in a computerized navigation system which can be, for example, generally represented by the structure shown in FIG. 9. All the vessels involved in a seismic WAZ acquisition can be equipped with the same navigation system which uniquely identifies each source and receiver defined in the project (mapping). The navigation system from each vessel shares information/data with the navigation systems from the other vessels. This is generally achieved through the use of redundant radio links. One of the navigation systems is defined as the Master. The Master system monitors, e.g., in real time, the positions—inline (dDA) and crossline (DC) distances along a predefined track in the form of a bull eye—and the firing orders of the other vessels which are defined as Slaves. The firing sequence (which defines the pattern for which a source fires on which shot) is managed by the Master navigation system based on the preplot information. The navigation setup has the ability to change the mapping (fire pattern), suspend or add any Slave vessel at any time.

Thus, a computerized navigation system **900** may receive, via the input/output interface **902**, information pertinent to positions of the sources and/or streamers, the arc angle, the turning radius, the run-in length, the run-out length, etc and may use this information to implement any of the configurations and/or seismic data acquisition methods described above. In addition, the computerized system **900** may include a processor **904** for processing the above-noted data and for calculating, for example, the size of a cell. The interface **902** and the processor **904** are connected to a bus **906**. Further, the computerized system **900** may include a memory **906** to store the above-noted data, a display **910**, a connection **912** to the streamers and/or the sources, and other elements common for a computerized system or server as would be recognized by those skilled in the art. It will be appreciated by those skilled in the art that FIG. 9 represents a generalization of an onboard navigation system used in conjunction with the various

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embodiments described herein and that such a navigation system may omit elements illustrated in the figure and/or include other elements.

The above-disclosed exemplary embodiments provide a system and a method for improving azimuth distribution for seismic data acquisition. It should be understood that this description is not intended to limit the invention. On the contrary, the exemplary embodiments are intended to cover alternatives, modifications and equivalents, which are included in the spirit and scope of the invention as defined by the appended claims. Further, in the detailed description of the exemplary embodiments, numerous specific details are set forth in order to provide a comprehensive understanding of the claimed invention. However, one skilled in the art would understand that various embodiments may be practiced without such specific details.

Among other variations and permutations associated with the foregoing embodiments, consider that although the foregoing embodiments illustrate the streamers being parallel to one another, such is not required. For example, in yet another exemplary embodiment the streamers may be provided to have a dovetail-like (fan) arrangement. According to still another exemplary embodiment, the streamers may have a variable depth along as described, for example, in patent application Ser. No. 13/272,428, entitled "Method and Device to Acquire Marine Seismic Data," and authored by R. Soubaras, the entire content of which is incorporated herein by reference. In one application, the streamers are fanned in a horizontal plane (substantially parallel to the water surface) so that they make an angle with each other. To achieve this arrangement, birds may be located on each streamer for maintaining the streamers at the desired positions. The birds are devices capable of maintaining a vertical and/or horizontal position in the water.

Although the features and elements of the present exemplary embodiments are described in the embodiments in particular combinations, each feature or element can be used alone without the other features and elements of the embodiments or in various combinations with or without other features and elements disclosed herein. Further, it is noted that the above embodiments may be implemented in software, hardware or a combination thereof.

This written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the subject matter is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

What is claimed is:

1. A survey acquisition system comprising:

a plurality of streamers towed by a plurality of streamer vessels, including a first streamer vessel and a second streamer vessel;

a plurality of sources towed by a plurality of source vessels, wherein said plurality of streamer vessels and said plurality of source vessels are configured relative to one another such that said plurality of source vessels are positioned at one or more predetermined inline distances behind a portion of the first streamer vessel and are also positioned at one or more predetermined inline distances in front of a portion of the second streamer vessel,

wherein said plurality of source vessels are positioned between the first streamer vessel and the second streamer vessel in the inline direction, and

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wherein said plurality of streamer vessels and said plurality of source vessels are also spaced apart from one another in a cross-line direction.

2. The system of claim 1, wherein said plurality of source vessels are each positioned at a different predetermined inline distance behind said portion of said first streamer vessel and at a different predetermined inline distance in front of said portion of said second streamer vessel.

3. The system of claim 1, wherein cross-line distances between adjacent streamer vessels and source vessels are the same.

4. The system of claim 1, wherein said plurality of source vessels are located in a cross-line direction between said first streamer vessel and said second streamer vessel.

5. The system of claim 4, wherein said one or more predetermined inline distances are consecutive multiples of a predetermined inline distance associated with a source vessel adjacent to said first streamer vessel.

6. The system of claim 1, wherein each of said plurality of streamer vessels and each of said plurality of source vessels is singularly attached to one of a plurality of tow lines.

7. The system of claim 1, wherein the first streamer vessel is positioned at (0,0), a first source vessel is positioned at (SW;-SL/3), a second source vessel is positioned at (SW\*2;-2\*SL/3), the second streamer vessel is positioned at (SW\*3;-SL), and a third source vessel is positioned at (SW\*4;-SL/2), where:

coordinates are expressed as relative (inline, cross-line) values,

SW=(a number of streamers per streamer vessel)\*(a separation between streamers)

SL=an adjusted streamer length.

8. The system of claim 7, wherein the adjusted length of the plurality of streamers is adjusted to be a multiple of 2, 3 and a shot point interval.

9. The system of claim 7, wherein the adjusted length of the plurality of streamers is adjusted to be a multiple of 2 and a shot point interval.

10. The system of claim 1, wherein the first streamer vessel is positioned at (0,0), a first source vessel is positioned at (SW;-SL/4), a second source vessel is positioned at (SW\*2;-2\*SL/4), a third source vessel is positioned at (SW\*3;3\*SL/4), and the second streamer vessel is positioned at (SW\*4;-SL), and where:

coordinates are expressed as relative (inline, cross-line) values,

SW=(a number of streamers per streamer vessel)\*(a separation between streamers)

SL=an adjusted streamer length.

11. The system of claim 1, wherein the plurality of streamers are variable depth streamers.

12. The system of claim 1, wherein the vessel configuration is used in a first pass associated with a first towing direction and the vessel configuration is inverted in a second, adjacent pass associated with a second opposite towing direction.

13. A method for seismic data acquisition, said method comprising:

configuring a seismic data acquisition system by:

positioning a plurality of source vessels at one or more predetermined inline distances behind a portion of a first streamer vessel,

positioning the plurality of source vessels at one or more predetermined inline distances in front of a portion of a second streamer vessel,

positioning the plurality of source vessels between the first streamer vessel and the second streamer vessel in the inline direction, and

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spacing said plurality of streamer vessels and said plurality of source vessels apart from one another in a cross-line direction; and

acquiring the seismic data using the configured seismic data acquisition system by shooting sources associated with the plurality of source vessels to generate acoustic signals and receiving reflected acoustic signals at streamers associated with said first streamer vessel and said second streamer vessel.

14. The method of claim 13, wherein said plurality of source vessels are each positioned at a different predetermined inline distance behind said portion of said first streamer vessel and at a different predetermined inline distance in front of said portion of said second streamer vessel.

15. The method of claim 13, wherein cross-line distances between adjacent streamer vessels and source vessels are the same.

16. The method of claim 13, wherein said plurality of source vessels are located in a cross-line direction between said first streamer vessel and said second streamer vessel.

17. The method of claim 16, wherein said one or more predetermined inline distances are consecutive multiples of a predetermined inline distance associated with a source vessel adjacent to said first streamer vessel.

18. The method of claim 13, wherein each of said plurality of streamer vessels and each of said plurality of source vessels is singularly attached to one of a plurality of tow lines.

19. The method of claim 13, wherein the first streamer vessel is positioned at (0,0), a first source vessel is positioned at (SW;-SL/3), a second source vessel is positioned at (SW\*2;-2\*SL/3), the second streamer vessel is positioned at (SW\*3;-SL), and a third source vessel is positioned at (SW\*4;-SL/2),

where:

coordinates are expressed as relative (inline, cross-line) values,

SW=(a number of streamers per streamer vessel)\*(a separation between streamers)

SL=an adjusted streamer length.

20. The method of claim 19, wherein the adjusted length of the plurality of streamers is adjusted to be a multiple of 2, 3 and a shot point interval.

21. The method of claim 13, wherein the first streamer vessel is positioned at (0,0), a first source vessel is positioned at (SW;-SL/4), a second source vessel is positioned at (SW\*2;-2\*SL/4), a third source vessel is positioned at (SW\*3;3\*SL/4), and the second streamer vessel is positioned at (SW\*4;-SL), and where:

coordinates are expressed as relative (inline, cross-line) values,

SW=(a number of streamers per streamer vessel)\*(a separation between streamers)

SL=an adjusted streamer length.

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22. The method of claim 21, wherein the adjusted length of the plurality of streamers is adjusted to be a multiple of 2 and a shot point interval.

23. The method of claim 13, wherein the plurality of streamers are variable depth streamers.

24. The method of claim 13, further comprising:

inverting the vessel configuration from a first pass associated with a first towing direction and a second, adjacent pass associated with a second opposite towing direction.

25. The method of claim 13, further comprising:

towing said seismic data acquisition system, for a first data acquisition, in one hundred eighty degree alternating directions across a mapping area until said mapping area is covered wherein each pass is separated by a predetermined pass distance while a shot is fired by one of said plurality of source vessels at a predetermined shot point interval; and

towing said seismic data acquisition system, for a second data acquisition intersecting said first data acquisition, in one hundred eighty degree alternating directions across said mapping area until said mapping area is covered wherein each pass is separated by said predetermined pass distance while a shot is fired by one of said plurality of source vessels at a predetermined shot point interval.

26. The method of claim 25, wherein said second data acquisition intersects said first data acquisition at a ninety degree angle.

27. The method of claim 25, wherein said first streamer vessel, said second streamer vessel and said plurality of source vessels are repositioned between each of said one hundred eighty degree alternating directions of said first data acquisition and said second data acquisition.

28. The method of claim 27, wherein said repositioning is equivalent to rotating said seismic data acquisition system one hundred eighty degrees around an axis perpendicular to the direction of travel and in the plane of travel.

29. The method of claim 25, further comprising:

towing said seismic data acquisition system, for a third data acquisition intersecting said first data acquisition and said second data acquisition such that any two data acquisition directions form a sixty degree angle, in one hundred and eighty degree alternating directions across said mapping area until said mapping area is covered wherein each pass is separated by said predetermined distance while a shot is fired by one of said plurality of source vessels at a predetermined shot point interval.

30. The method of claim 29, wherein said shot is fired in a round-robin fashion by each of said plurality of source vessels.

31. The method of claim 13, wherein said sources are shot using a different time interval for each of said plurality of source vessels.

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